Final Report

Joint Industry Project

DESIGN OF CATHODIC PROTECTION RETROFITS FOR OFFSHORE STRUCTURES – Part II: Recommended Practice

submitted by

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I. Forword

This report presents a recommended practice for design of cathodic protection (cp) retrofits for fixed offshore petroleum production structures. The practice is based upon results of a three year joint industry research project entitled, *Design of Cathodic Protection Retrofits for Offshore Structures*, with the present document serving as Part II of the Final Report. Background information and justification for the proposed practice can be found in Part I (1).

A need to retrofit can arise from any one or combination of causes, including 1) initial under-design, 2) damage from causes such as storms and duty improprieties, and 3) anode wastage over time. The first of these factors (initial under-design) is not addressed explicitly; but the recommended practice is applicable to such situations in some cases. In this regard, the data upon which the practice is based were developed from experiments and analyses that assumed that the structure in question was either adequately polarized at one time or that it remains polarized. Consequently, this practice is not intended for structures or portions of structures that have never received adequate protection. An example is the conductor guide area of a structure that is elsewhere marginally protected, since shielding can result in under-protection for the former (conductor area). For such situations, it is recommended that practices that pertain to new structures (2,3) be employed. The second cause for a need to retrofit (damage from factors such as storms or duty improprieties) is likely to arise primarily in conjunction with impressed current cathodic protection (iccp) systems; however, the great majority of cp systems on offshore structures are of the galvanic type. While the retrofit cp design portion of this recommended practice is applicable to iccp, it is considered that galvanic anode wastage is the issue at hand in most cases; and it is upon this that attention was focused.

The approach that was adapted considered the overall cp retrofit process in terms of three components as listed below:

1. Criteria for Determining When a Cathodic Protection Retrofit Is Needed.

2. Retrofit Design Alternatives and Procedures.

3. Time-To-Retrofit for Structures That Are Still Polarized.

Factors such as type of retrofit, (impressed current versus galvanic or hybrid, and materials and hardware specifications (anode selection and type of mounting (string, sled, or clamp/welded, for example))) are not addressed.

II. Criteria for Determining When a Cathodic Protection Retrofit Is Needed.

Steel in sea water corrodes at an unacceptable rate when potential, ϕ, is positive to (greater than) -0.80 $V_{Ag/AgCl}$; and corrosion is arrested when $\phi \leq -0.80$ $V_{Ag/AgCl}$ (2,3). However, the optimum potential range for protection has been shown to be $-1.05 < \phi \leq$ -

0.90 $V_{Ag/AgCl}$, since within this current density to affect the prescribed polarization is minimum (4,5). Three criteria were identified for defining if the cp system on a particular structure should be retrofitted. The first two are based upon structure potential being positive in different degrees to the above ideal range, whereas for the third potential could be in the ideal range but with concerns regarding remaining anode mass and structure age taking precedence. Each of these three criterion is described below.

A. Potentials Positive To –0.80 $V_{Ag/AgCl}$.

By this criterion, cp retrofitting is required if potential is determined to be positive to -0.80 $V_{Ag/AgCl}$. This applies to the structure potential in question being the mean value or that of individual zones or localized areas. If only an individual zone or localized area is corroding, then the retrofit can be applied to that location only. However, since any corrosion is normally unacceptable, intervention is desired prior to potential becoming positive to -0.80 $V_{Ag/AgCl}$ such that options B and C are preferred, as explained below.

B Positive Potential Drift.

This criterion requires retrofitting if structure potential, as determined by the preceding survey, is determined to be in the ideal range for protection ($1.05<\phi\leq-0.90$ $V_{Ag/AgCl}$) and for the present or most recent survey to be between –0.90 and –0.80 $V_{Ag/AgCl}$. Such a potential movement normally results because of extensive galvanic anode consumption such that anode resistance has increased to such a level that loss of protection ($\phi >$ -0.80 $V_{Ag/AgCl}$) is eminent. The positive potential drift criterion is likely to avoid the corrosion that invariably results if the –0.80 $V_{Ag/AgCl}$ criterion (see above) is employed.

C. Anode Wastage-Structure Age.

This criterion is based upon the fact that remaining life of galvanic anodes is governed by 1) maintenance current density (i_{maint}) and 2) maintenance current capacity (C_{maint}) of galvanic anodes. The term "maintenance" refers to the present value for the indicated parameter as opposed to the mean or time-averaged value. In general, i_{maint} and C_{maint} decrease with time (1). Thus, it can be reasoned that if anodes on a 12 year old structure are 80 percent wasted, then only three years or less remain for complete expiration (utilization factor neglected). The structure may still be fully polarized, but the prudent approach would be to proceed with planning for cp retrofit. In the same situation for a 30 year old structure, it can be reasoned that as long as 7.5 years remain until complete anode wastage.

The Appendix presents a protocol whereby 1) i_{maint} and 2) remaining anode mass (w_r) can be determined from potential survey and dimensional data, respectively. By determining these for two surveys (for older structures i_{maint} should be relatively constant for the time period of two contiguous surveys) and knowing structure surface area, A_c, and the time between the two surveys, ΔT, C_{maint} can be calculated from the mass balance expression

$$C_{maint} = \frac{i_{maint} \cdot A_c \cdot \Delta T}{\Delta w_r}, \qquad (1$$

where Δw_r is the mean difference in remaining anode weight between the two survey times. The remaining useful life of the cp system (time-to-retrofit) is plotted as a function of $i_{maint} \cdot A_c / C_{maint}$ and for different values of w_r in Figure 1.

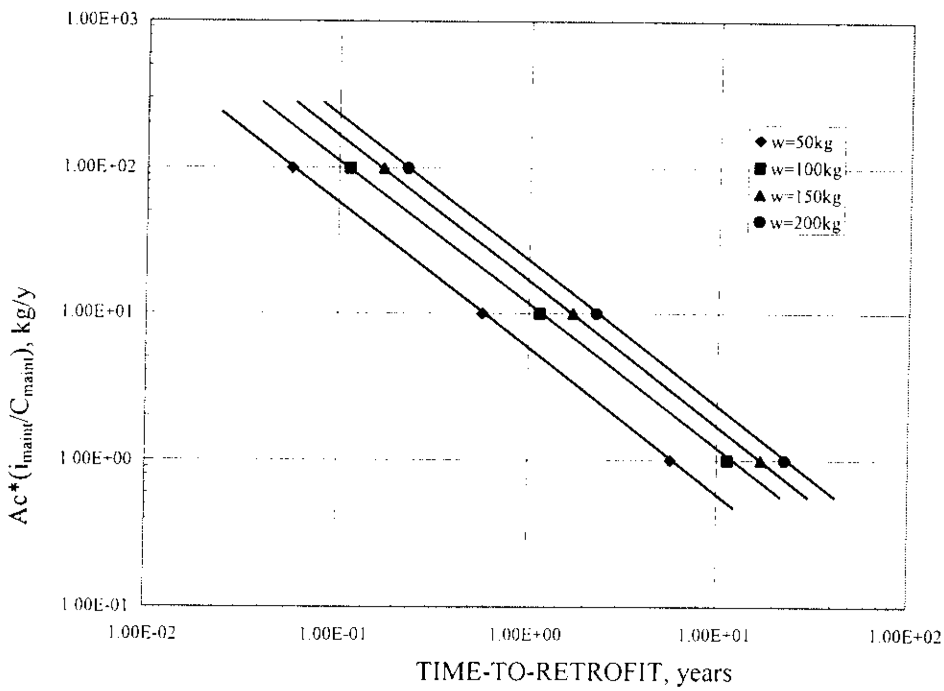

Figure 1:Plot of time-to-retrofit for remaining anode weights of 50, 100, 150, and 200 kg as a function of $i_{maint} \cdot A_c / C_{maint}$.

It is important to recognize that i_{maint} and C_{maint} for older structures have both been reported to be less than is assumed in the cp design specifications for new structures (2,3). For example, the mean i_{maint} for two Gulf of Mexico (6) and 15 Arabian Gulf (7) structures (ages 6-26 years) was 13.4 mA/m^2 with a standard deviation of 7.8 mA/m^2. Likewise, Keifer et al. (7) reported C_{maint} for these same Arabian Gulf structures as only 106 Ah/kg with a standard deviation of 79 Ah/kg.

III. Retrofit Cathodic Protection Design Alternatives.

A. Method Description.

Experimental data (1) indicate that fewer anodes are required for a cp retrofit than for an initial design (new structure) provided that the structure was adequately polarized at one time. Consequently, a cost savings that is substantial in the case of large, deep water structures can be realized. Alternatives for the design of such retrofits are presented below.

A key parameter in retrofit cp design is the structure current or current density demand (i_{maint}), since the required number of retrofit anodes is likely to vary in direct proportion to this. As an example of the structure-to-structure variation that is likely to exist for this parameter, i_{maint} for the two Gulf of Mexico and 15 Arabian Gulf structures cited above (6,7) ranged from 3.4 to 34.4 mA/m^2. The Appendix provides a recommended protocol for determining i_{maint} on existing structures that are retrofit candidates.

1. Structures That Remain Polarized.

For structures whose potential remains in the ideal potential range ($1.05<\phi\leq -0.90$ $V_{Ag/AgCl}$), retrofit anodes can be designed according to the modified form (1) of the unified design equation (4,5,8),

$$w \cdot R_a = \frac{i_{maint} \cdot e^{0.032 \cdot T} \cdot T \cdot S}{2{,}598 - k_c \cdot \sigma_c}, \qquad 2)$$

where

w is weight of an individual anode,
R_a is resistance of an individual anode,
T is the design life of the retrofit system,
S is the slope parameter (this may be taken as $(\phi_c-\phi_a)/i_{maint}$), where ϕ_c and ϕ_a are the polarized structure and anode potentials, respectively,
σ_c is the standard deviation for current capacity, and
k_c is a factor of safety for current capacity.

The required number of anodes, N, is then determined from the equation (4)

$$N = \frac{R_a \cdot A_c}{S}. \qquad 3)$$

2. Structures That Have Partially or Fully Depolarized.

For structures that have partially depolarized but which are still protected ($\phi\leq -0.80$ $V_{Ag/AgCl}$), the steady-state current density upon repolarization, $i_{maint(rep)}$, is projected from the partially depolarized maintenance current density, $i_{maint(dep)}$, using the expression (9),

$$i_{maint(rep)} = 1.47 i_{maint(dep)} + 3.53 + k\sigma_{maint(rep)}, \qquad 4)$$

where $\sigma_{maint(rep)}$ is the standard deviation for $i_{maint(rep)}$ (5.19 mA/m^2) and k is a factor of safety for this parameter (all current densities are in mA/m^2). In the case of fully depolarized structures, it may be possible to calculate the i_{maint} that existed prior to depolarization, $i_{maint(pre)}$, from past potential survey results in which case $i_{maint(rep)}$ is defined by

$$i_{maint(rep)} = i_{maint(pre)} + k\sigma_{maint(rep)}. \qquad 5)$$

If insufficient pre-depolarization data are available, then the mean i_{maint} from the structures in references 6 and 7 may be substituted for $i_{maint(pre)}$. Thus,

$$i_{maint(rep)} = 13.4 + k\sigma_{maint(pre)}. \qquad 6)$$

The initial current density for repolarization, $i_{o(rep)}$, on the other hand, is given for partially depolarized structures by the expression (9)

$$i_{o(rep)} = 2.31 \cdot (1.47 \cdot i_{maint(dep)} + 3.53 + k\sigma_{ma\,int(rep)}) + 32.47 + k\sigma_{io(rep)}, \qquad 7)$$

where $\sigma_{o(rep)}$ is the standard deviation for $i_{o(rep)}$ (17.33 mA/m^2), and k is a factor of safety on $i_{o(rep)}$. Corresponding expressions that pertain to fully depolarized structures are

$$i_{o(rep)} = 2.31(i_{maint(pre)} + \mathrm{k}\sigma_{maint(rep)}) + 32.47 + k\sigma_{io(rep)} \qquad 8)$$

or

$$i_{o(rep)} = 2.31 \cdot \left(13.4 + k\sigma_{ma\,int(pre)}\right) + 32.47 + k\sigma_{io(rep)}. \qquad 9)$$

Upon knowing values for $i_{o(rep)}$ and $i_{maint(rep)}$, a reformulation of Equation 2 as

$$w \cdot R_a = \frac{i_{ma\,int(rep)} \cdot e^{0.032 \cdot T} \cdot T \cdot S}{2{,}598 - k_c \cdot \sigma_c}, \qquad 10)$$

where S is now defined as $(\phi_{c(o)}-\phi_a)/i_{o(rep)}$, is employed for anode design and Equation 3 to determine the required number of anodes.

The advantage of this approach compared to those in standards for design of cp systems for new structures (2,3) is that the required number of anodes is less because values for $i_{o(rep)}$ and $i_{maint(rep)}$ are less.

B. Relatively Small Structures.

In the case of relatively small structures with few anodes, the time and expense of a retrofit cp design may exceed the material and installation costs of simply adding new anodes as a one-to-one replacement of the existing ones. In such situations, the one-to-one replacement approach should be employed.

As an alternative to one-to-one replacement or to a retrofit design based upon Equation 10, a simplified design approach can be used that consists of the following steps:

1. Determine from survey information the average anode mass that has been consumed ($w(T_1)$), where T_1 is the time at which the structure is to be retrofitted.

2. From knowledge of A_c, N, and T_1 and having determined $w(T_1)$, calculate the ratio of C_m to i_m using the mass balance expression

$$\frac{C_m}{i_m} = \frac{w(T_1) \cdot N}{A_c \cdot T_1} . \qquad 11)$$

3. Using the value for C_m/i_m from 1) and from knowledge of R_a and the original anode weight, w_o, from the original design, solve the modified unified design equation,

$$S = \frac{C_m \cdot R_a \cdot w_o}{i_m \cdot T_1} , \qquad 12)$$

   for the effective S of the original design.

4. Using the values for S and C_m/i_m, as determined above, and letting $T_2 - T_1$ be the design life of the retrofit cp system (T_2 is the age of the platform at the end of the retrofit cp system design life), reapply the unified design equation to determine the anode design (R_a. w). Thus,

$$R_a \cdot w = \frac{i_m}{C_m} \cdot S \cdot (T_2 - T_1) . \qquad 13)$$

   This analysis may incorporate a factor of safety in that C_m of present anodes is probably greater than for earlier ones.

5. The number of anodes is then determined from Equation 3.

IV. Time-To-Retrofit for Structures That Are Still Polarized.

The approach here involves a modification of what was presented under retrofit criterion C (see above) and involves the following steps:

A. Using the protocol in the Appendix, determine i_{maint}.

B. From the equation for the time dependence of i_{maint} (1,10),

$$i_{maint} = 10^{(a+k_i \cdot \sigma_i)} \cdot T_1, \qquad 14)$$

where a is a constant, k_i is constant for a particular structure that reflects the extent to which i_{maint} deviates from the mean, and σ_i is the standard deviation for a, and from knowing the structure age, T_1, calculate k_i. Values for a and σ_i are listed in Table 1.

Table 1: Equation 14 parameters for warm and cold/deep water exposures.

	Warm Water	Cold/Deep Water
a	1.510	1.929
σ_i	0.233	0.229

C. Determine the average anode weight loss, $w(T_1)$, either based upon diver estimated depletion or from the Appendix protocol. Calculate C_m using the expression

$$C_m = \frac{i_m \cdot A_c \cdot T_1}{N \cdot w(T_1)}. \qquad 15)$$

D. Using the equation

$$C_m = (2{,}598 - k_c \cdot \sigma_c) \cdot e^{-0.032 \cdot T_1}, \qquad 16)$$

and the value for C_m from Step C, calculate k_c.

E. Solve the expression

$$w(T_1) - w_o \cdot f_u(T_2) = \frac{8.76 \cdot 10^{(a+k_i \cdot \sigma_i)} \cdot A_c}{N \cdot (b+1) \cdot (2{,}598 - k_c \cdot \sigma_c)} \cdot$$

$$\left[\left(T_1^{b+1} \cdot e^{0.032 \cdot T_1}\right) - \left(T_2^{b+1} \cdot e^{0.032 \cdot T_2}\right)\right] \qquad 17)$$

for T_2, the time at which the useful life for the anodes will be reached, by substituting values for $w(T_1)$, k_i, and k_c, as determined above, knowing N, A_c, and w_o, and selecting an appropriate value for f_u, the anode utilization factor. The remaining anode life is then determined as $T_2 - T_1$.

IV. Bibliography

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Appendix

Protocol for Field Survey Assessment Of Structure Current Demand (Maintenance Current Density) and Maintenance Current Capacity of Galvanic Anodes

I. Background

Determination of structure current demand (alternatively, maintenance current density, i_{maint}) is critical for designing cp retrofits and both this parameter and maintenance current capacity, C_{maint}, are important for projecting when a cathodic protection (cp) retrofit should be performed. The protocol provided herein gives guidelines for current demand determinations according to two procedures, each of which has been qualified as appropriate. The first of these is based upon direct measurement of current through each of the two anode standoffs using a Gaussian ammeter (Swain meter), and then summing these to give the net anode current output. The second procedure, termed the *$\Delta\phi$-MDE* (potential difference–modified Dwight equation) method, incorporates field measurements and a first principles based calculation procedure. Also described is a method for estimating remaining anode mass. From this, the mean current capacity, C_m, can be determined. If remaining anode mass is determined during two surveys, then C_{maint} can be estimated.

II. Determination of Structure Current Demand

A. Gaussian Ammeter

In this case, measurements are made directly by a diver using a hand held clip that is positioned about the anode standoff with the current reading being recorded topside. Six readings should be taken for each standoff, three with the clip in both the forward orientation and three in the reverse (flipped 180°). The absolute value of these readings is then averaged to give the current through the standoff. Measurements should be made for a statistically significant number of anodes with consideration being given to spatial variability. Both the clip and cabling, as presently manufactured, are not particularly rugged; and so consideration must be given to protection of these components. The procedure is not conducive to ROV based measurements because of mechanical damage that invariably occurs in positioning and maintaining the clip about standoffs. The Swain Company is the sole manufacturer of this instrumentation, and the relatively new MER (magnetic error reduction) meter model should be employed. The meter should be tested for accuracy/calibration prior to the survey and at least daily during the survey and at completion.

B. *$\Delta\phi$-MDE* Method

Potential measurements are made along the length of individual anodes at six to eight positions. This is done by placing the reference electrode directly upon the fouled anode surface. Measurements should be acquired for a statistically significant number of anodes with consideration being given to any spatial variability (different zones on the structure). Length and thickness of the anode, including the thickness of any fouling layer, are determined either by direct measurement or by sizing relative to a known dimension (standoff or tubular member, diver's hand, tool, or ruler). This determination should be video recorded, and the measurement can even be made from the video.

A structure potential measurement is taken remote from the anode but in its general vicinity and at approximately the same depth. Water resistivity at this same depth is measured.

The anode-structure potential difference, $\Delta\phi$, is calculated as

$$\Delta\phi = \phi_c(\text{remote}) - \phi_a(\text{min}), \qquad \text{(A1}$$

where

ϕ_c(remote) is the remote structure potential and
ϕ_a(min) is the most negative potential recorded for the anode in question.

The anode resistance, R_a, is determined using the modified Dwight' equation,

$$R_a = \frac{\rho}{2\pi l} \cdot \left[\ln\left(\frac{2l}{r} \right) - 1 \right], \qquad \text{(A2}$$

where

ρ is water resistivity,
l is anode length, and
r is the effective anode radius (including thickness of any fouling layer).

The current output, I_a, of an individual anode is then determined from the expression

$$I_a = \frac{\Delta\phi}{R_a}. \qquad \text{(A3}$$

The average current output for the surveyed anodes on the structure (alternatively, for a zone of the structure), $\bar{I}_a$, is determined, and the net anode current output, I_t, for the structure or zone is calculated from the equation

$$I_t = \bar{I}_a \cdot N, \qquad \text{(A4}$$

where N is the number of anodes, either on the entire structure or in the zone under consideration). Alternatively, i_{maint} can be calculated from the expression

$$i_{ma\,\mathrm{int}} = \frac{\bar{I}_a \cdot N}{A_c}, \qquad \text{(A5}$$

where A_c is the structure surface area.

III. Determination of Remaining Anode Weight.

Remaining anode weight is determined by cleaning, either local areas or complete anodes and measuring the remaining radius, diameter, or circumference. From this, the weight, w, is calculated as the product of anode volume (minus the core volume) and density. Measurements should be made for a statistically significant number of anodes with consideration being given to spatial variability.